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AN EXTENDIBLE BOOM SYSTEM FOR SPACE VEHICLES

A REPORT

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SPECIAL PRODUCTS & APPLIED RESEARCH DIVISION
THE DE HAVILLAND AIRCRAFT OF CANADA LIMITED
MALTON ONTARIO CANADA

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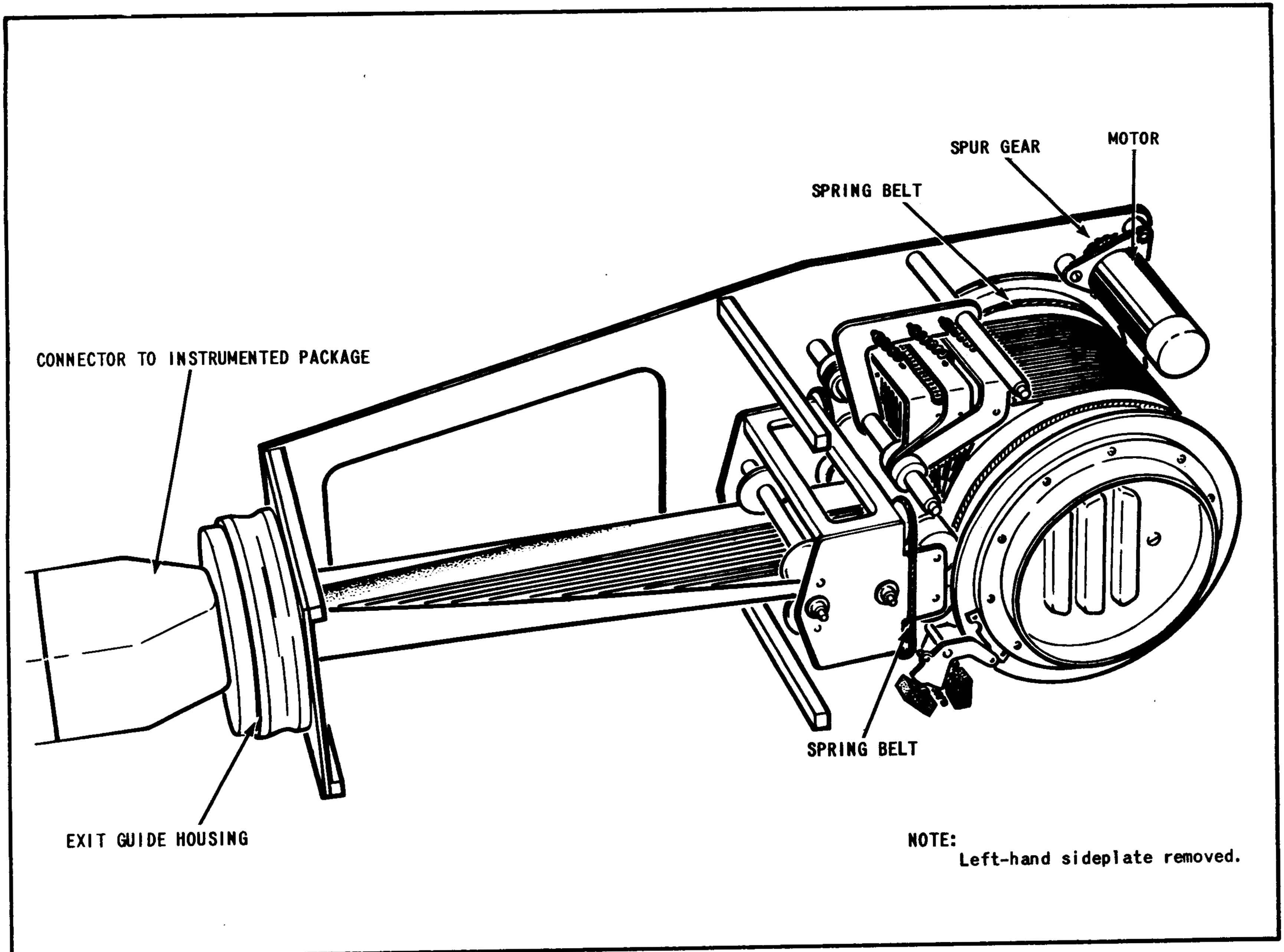

Frontispiece. The Proposed Boom System--General Layout.

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AN EXTENDIBLE BOOM SYSTEM FOR SPACE VEHICLES

A REPORT

Dated: 30 January, 1963

Prepared by the staff of the Engineering Department

Special Products & Applied Research Division

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ABSTRACT

The report describes a suitable means by which a magnetometer or similar instrument may be protruded from a carrier-vehicle in space flight. The proposed system resulted from a design study of an existing principle; namely, a storage drum and guidance device that pays out a heat-treated metal strip which then assumes tubular configuration. Tape-type conduits are shown to be the most satisfactory form of internally located cable pack. A novel technique is adopted to provide the electrical link between the stationary and moving components. An interesting feature of the design appears in the very low power output required to drive the mechanism.

AUTHOR

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SECTION 1

INTRODUCTION

GENERAL

1.1 This report describes the design of a boom system that resulted from an engineering study. The body of the document comprises six Sections and two Appendices, and presents recommendations on the approach to practical and feasible applications of the system.

PURPOSE

1.2 The purpose of the investigation was to disclose and propose a suitable means of extending a boom from a carrier-vehicle in space flight, upon the end of which boom could be mounted a magnetometer or similar instrument package. The program was sponsored by Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), and was run in accordance with their Specification No. 63-49, dated 16 January, 1962, entitled 'Specifications for Development of Boom Erection System'.

DESIGN REQUIREMENT

1.3 In general terms, the boom was to be 21 feet in length when extended, and of non-magnetic material; to be capable of supporting a non-collapsible 72-inch tubular section and the instrument package in conditions of zero-'g' only; and was to run out an internally located cable pack. The basic design was to feature the 'Stored-Tubular-Extendible Member' (STEM) principle, as developed by de Havilland Aircraft of Canada--a technique that employs a storage drum and guidance device to pay out and form a heat-treated metal strip into a self-retaining tubular structure. The precise design requirements are listed in APPENDIX I.

1.4 A brief history of 'STEMs' and some of their uses, together with a synopsis of their design and performance, is contained within APPENDIX II. Where applicable, the data contained therein have all been incorporated in the design of the unit that is proposed in this report.

1.5 A similar unit to that of this report has already been produced. Photographs of the unit--the Type A-26--are inserted at the end of APPENDIX II. The main difference between the two units will be seen in the number of electrical conduits; the A-26 having one only. The boom system that this report describes, results from a development of the A-26 design principles.

SECTION 2

DESCRIPTION

GENERAL

2.1 The boom system as envisaged in the study (see Frontispiece) consists of the following main components; the boom and its internally located signal and electrical conduits (three individual conductor tapes); the strip feed-and-guide mechanism; the storage drum assembly; the drive mechanism; the terminal boards and connectors; and the mounting chassis. The following paragraphs describe the layout and function of each main component and its secondaries, and include operating characteristics only insofar as the description of a function requires; the operating characteristics are described fully in SECTION 3. In establishing the location of components, the unit is viewed from the rear--facing the direction of boom extension--or from the side having the direction of extension to the left-hand.

CHASSIS

2.2 The chassis is of simple construction and consists of two aluminum alloy sideplates and the necessary spacers. Attachment points for mounting the unit in the carrier-vehicle consist of two lugs at the forward end, and a spigot on each end of the drum assembly (outboard of the sideplate).

THE BOOM

2.3 The boom is manufactured in beryllium copper and originates as a flat strip 4.0 inches wide by 0.005 inch thick. The strip is heat-treated into tubular form; the edges then overlap by 10 degrees of arc; the nominal diameter is then 1.25 inches; the effective length, when extended, is 21 feet $\pm$ 0.03 inch. In the retracted (stored) condition, the boom is reverted to its strip configuration and is wound onto the storage drum (refer to paragraph 2.13).

2.4 The cross section of the tube (see Figure 2-1) is not exactly circular; the maximum deviation being toward the outermost edge of the strip, where the radius of curvature is greater than the nominal radius of the tube. The edges of the strip do not come into contact with each other, and so eliminate a source of frictional distortion and hysteresis; however, the overlap is sufficient to prevent the direct exposure of the conductor tapes to the effects of external radiation, radio 'noise', and micro-meteoroid collision.

2.5 Choice of boom dimensions was particularly related to the ability of the structure and its material to convey the conduits and withstand ground-handling loads.

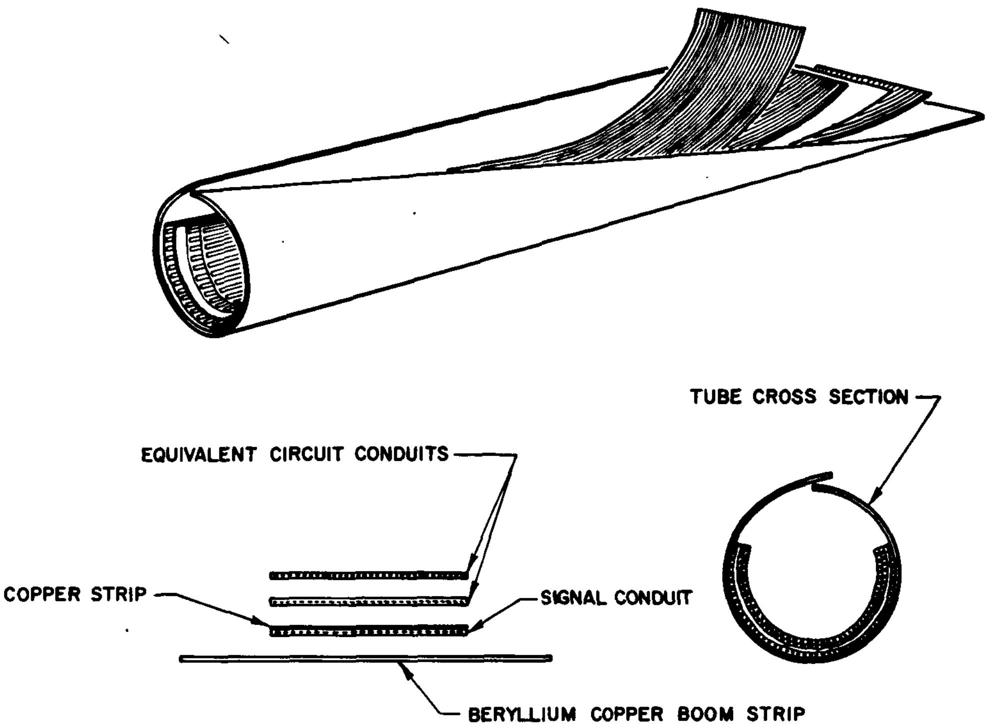

Figure 2-1. Boom and Conductor Tapes--Configuration and Arrangement.

Conductor Tapes

2.6 The details of the required cable pack are shown in APPENDIX I. Because of the difficulties encountered in the handling of grouped wiring--erratic behaviour of the cabling during 'feed', and a weight penalty induced by a necessarily larger unit--a departure from the Specification is proposed; namely, a substitution of the wires and Microdot cable by tape-type conduits (see Figure 2-1).

2.7 Each conduit (conductor tape) is composed of two layers of Mylar plastic strip, sandwiching ribbon-conductors of dead-soft copper. In the case of the equivalent circuit conduits, the layers of Mylar tape are each 0.001-inch thick; the copper ribbons are 0.063-inch wide by 0.002-inch thick. Twenty conductors can be arranged in a 2-inch wide tape, and two such tapes are used; so providing for circuits in excess of the number required.

2.8 In replacing the Microdot signal cable by conductor tape, it was assumed that a common ground is acceptable for these circuits. The 2-inch wide Mylar tape, in this case, is 0.004-inch thick per layer; the copper conductors are of the same dimensions as those above; twelve such ribbons are spaced at 0.15-inch (centre-to-centre) within the sandwich. A shield of 0.002-inch thick copper sheeting is bonded to one exterior surface of the sandwich. Due to the very small side area of the conductors, there is little cross-talk between channels. The tape is arranged within the boom, with the unshielded surface of the pattern facing the boom inner surface. If, then, the copper sheeting and the beryllium copper boom are used as ground, the circuits, therefore,

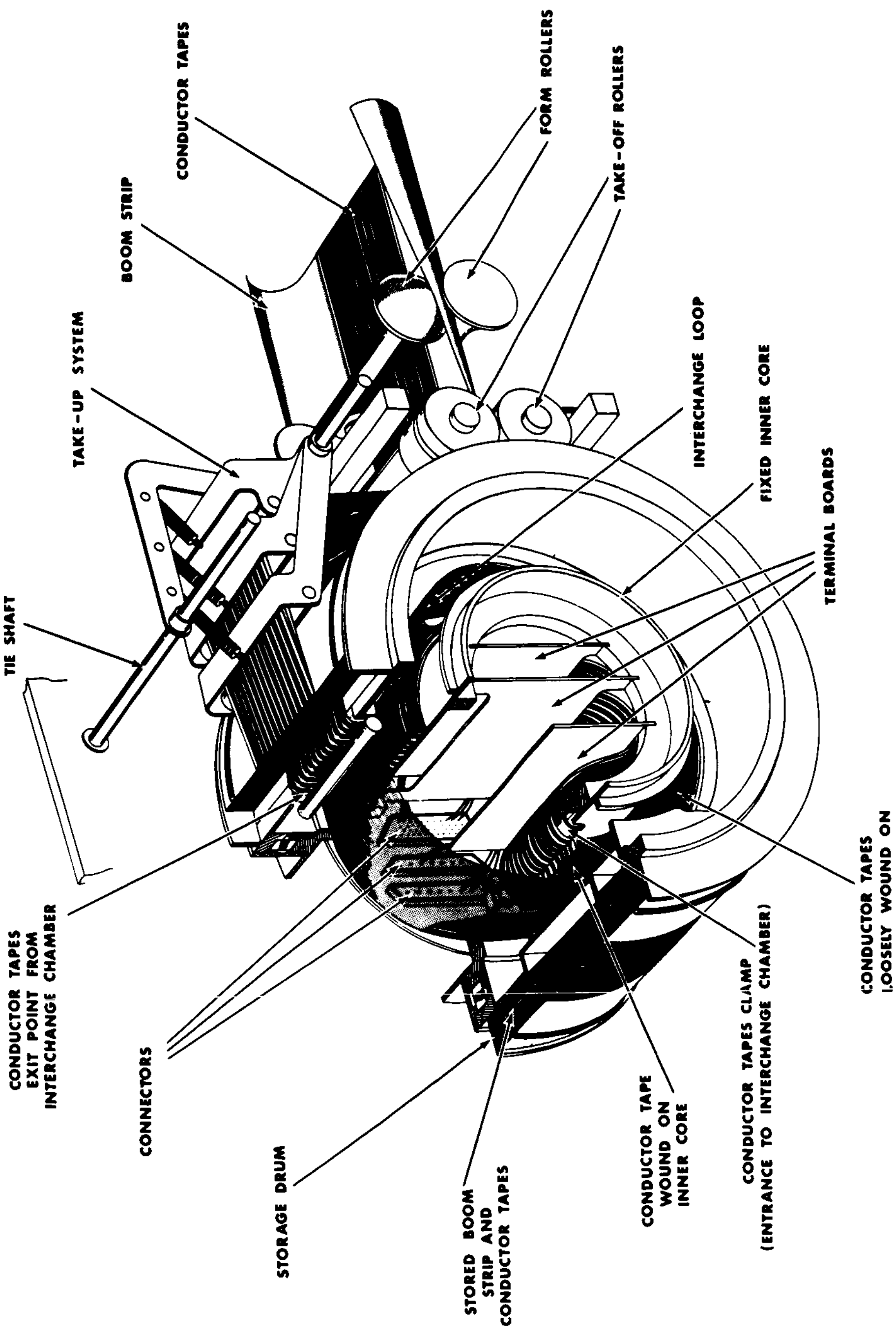

Figure 2-2. Cutaway View of Storage Drum.

are shielded from any external 'noise sources. Tests on this type of Microdot replacement are being conducted by a reliable electronics consultant.

Connectors and Connections

2.9 Connection between the conductors and the external connectors is made by use of an intermediate printed-circuit board and conventional wiring--where the conductor tape can be dip-soldered or welded to the printed circuit. If particular limitations exist with respect to available space, the printed circuit can be formed into complex shapes, as necessary. If standard terminals and flying leads are used to accomplish the union with the connectors, then standard approved connectors can be employed, and, if necessary, complex routing of the wiring can be effected. Because it utilizes the minimum in 'exotic' hardware, this latter method is best suited to small production wires of inexpensive cabling.

2.10 The technique of wiring flexible leads direct to the conductor tapes is now being investigated by de Havilland. A potting compound or a foam will be used to support the wire and the tape at the soldered or welded juncture.

2.11 If a common ground is used, it is possible to connect the shielded conductors to a Microdot connector bank. Should this requirement become necessary, the special terminals for the hook-up could be designed.

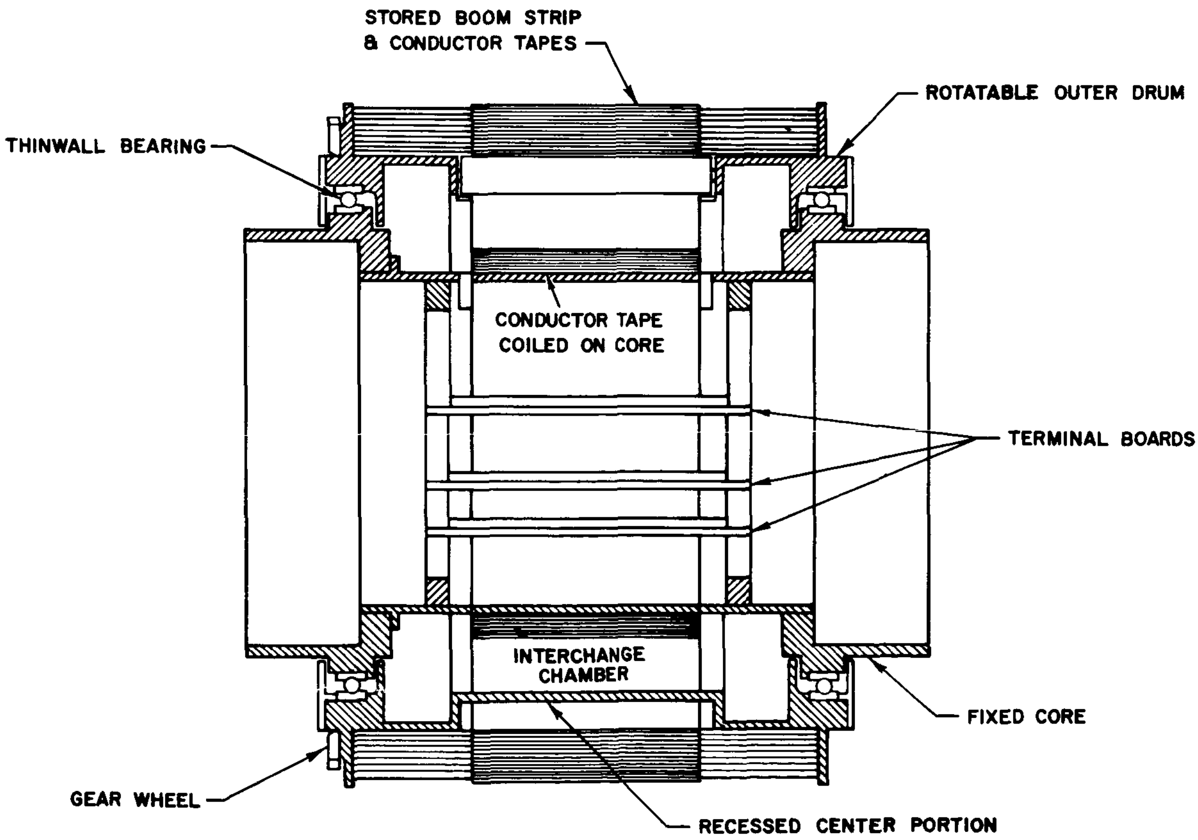

Figure 2-3. Cross Section of Storage Drum.

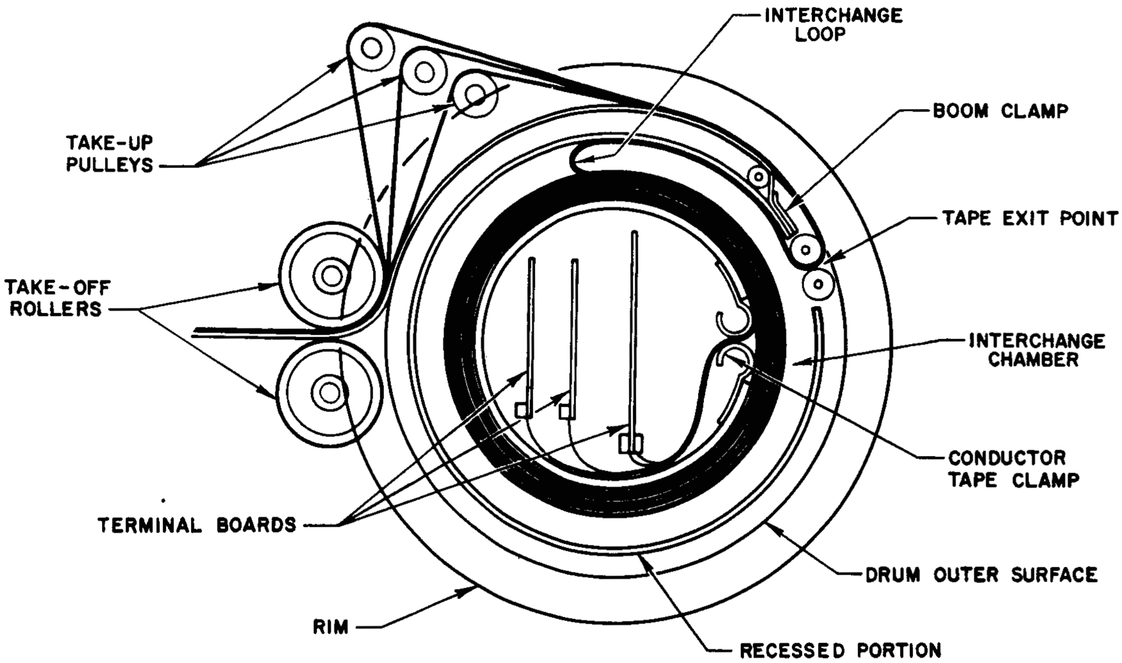

Figure 2-4. Method of Winding On Boom and Conductor Tapes.

STORAGE DRUM

2.12 The storage drum (see Figures 2-2 and 2-3) is, in effect, two cylinders--one within the other--and is manufactured in aluminum alloy. The smaller cylinder (core) is attached, through a hub assembly, to the sideplates of the chassis and remains stationary. The larger cylinder (the main storage drum) is free to rotate about the same hub assembly by means of thinwall bearings in each rim. The internal cavity between the core and the drum is termed 'the interchange chamber . The centre portion of the drum exterior surface is recessed and contains both the clamp to anchor the root end of the boom, and a slot and clamp through which the conductor tapes emerge from the interchange chamber. The core contains a slot and clamp through which the tapes are routed to circuit boards within.

Stowage of Boom and Conductor Tapes

2.13 Stowage of the boom and conductor tapes is best described by commencing with the element fully extended, and with reference to the left-hand side view shown in Figure 2-4.

2.14 The root of the boom strip is clamped to the drum. The conductor tapes are laid along the strip, one atop the other; the ends are inserted through the slot to the rear of the boom clamp, and into the interchange chamber. If the drum is now reversed, the boom strip and conductor tapes will be wound on as one strip. It will be appreciated that, due to the difference in radii between the boom strip and the individual conductor tapes when stored, the length of each conductor tape is increased in proportion. This fact has a direct bearing on the design of the feed-and-guide mechanism (described later in paragraph 2.20).

Interchange Chamber

2.15 The interchange chamber and the method of running through the electrical connections are the result of a practicable design. Some means had to be provided for bridging the gap between the fixed and rotating circuits; because of vacuum welding, slip-rings were unacceptable for spacecraft application. Additionally, there were the problems of 'noise' interference and the necessity of retaining simplicity in design. The interchange chamber method satisfies the requirement.

2.16 Assuming the ends of the conductor tapes to be one strip, and still assuming the boom to be fully extended, the surplus tape enters the interchange chamber and is coiled onto the core (see Figure 2-4), is passed through the slot (and the clamp), and the connection to the circuit boards is made. The loop between the entrance point from the drum and the start of the coil is termed 'the interchange loop'. When the drum is turned to completely wind on the boom and the conductor tapes, the core winding peels off and rewinds in a reverse direction. This operation is described in SECTION 3.

FEED-AND-GUIDE MECHANISM

2.17 The feed-and-guide mechanism (see Figures 2-2, 2-4, 2-5, and 2-6) consists of the take-off rollers, the form rollers, an exit guide, the take-up system, and a follower-and-cam type stop for the storage drum.

Rollers

2.18 The take-off rollers comprise a trolley assembly. The trolley is mounted on stainless steel flanged bearings; the bearings run in fore-and-aft slots in the sideplates. Two stainless-steel coil-spring belts pass around the drum--one along each edge of the boom strip--and over pulleys on the trolley. These belts maintain the take-off rollers in a rearward position, against the drum-wound strip, as the storage diameter decreases during extension of the boom. The specific function of the two sets of aluminum alloy rollers is to retain the boom strip and conductor tapes in manageable shape and correct positioning during the peeling-off-the-drum stage; a need that arises from the inherent tendency of the boom to immediately assume tubular form when freed from the drum (this characteristic is later described in SECTION III.

Exit Guide

2.19 An additional guide (see Figure 2-5) is provided at the exit from the chassis and is located approximately one foot from the take-off rollers. This guide is a disc-shaped cradle, manufactured in Teflon, and free to rotate upon thinwall bearings.

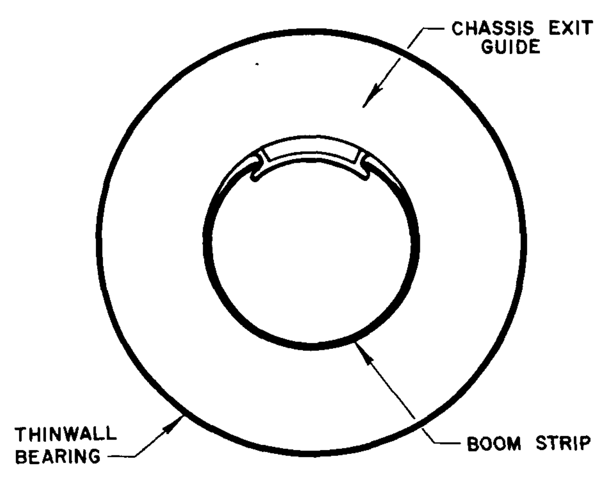

Figure 2-5. Exit Guide.

Take-up System

2.20 The take-up system is an aluminum alloy gantry assembly of three aluminum alloy roller-type pulleys over which the conductor tapes are individually routed prior to being paid out through the take-off rollers. This feature is introduced to compensate for the difference in tape lengths (refer to paragraph 2.14).

2.21 The pulleys have a common pivot point and are individually spring-loaded to the gantry. With the conductor tapes stowed, the springs are under minimum tension.

Follower and Cam

2.22 The follower-and-cam type stop (see Figure 2-6) is provided as a means of braking and arresting the rotation of the drum in such a manner that the boom is extended to the specified length with accurate repeatability.

2.23 A stainless-steel two-stage cam is located at the left-hand rim of the drum; a slot is cut in the drum circumference, just inboard from the rim; both are at approximately 140 degrees clockwise following the root clamp of the boom.

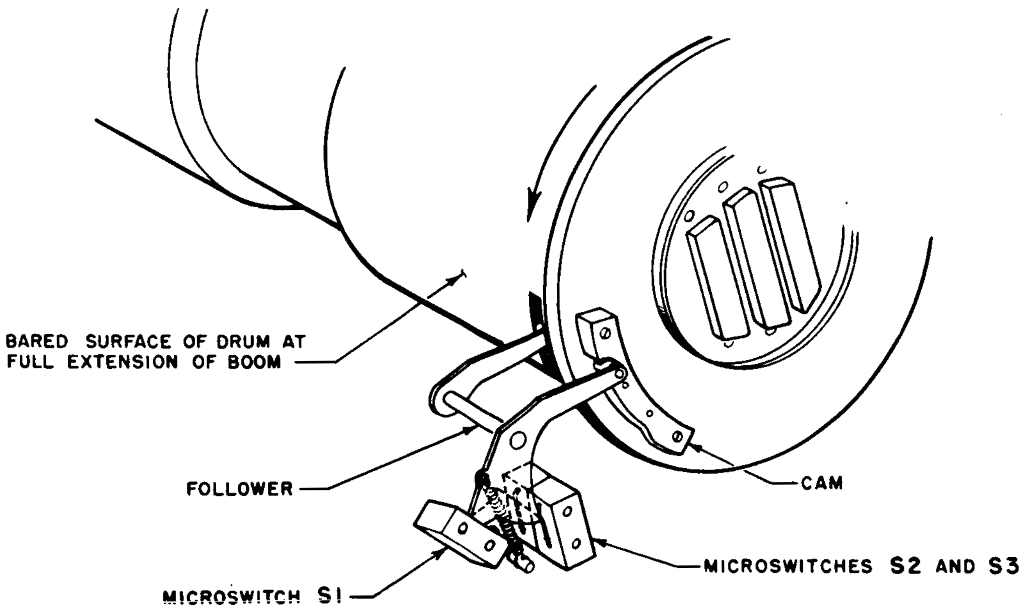

Figure 2-6. Follower and Cam.

2.24 The follower is a pair of aluminum alloy bellcranks, each mounting a roller--one running directly in line with the slot in the drum, the other in line with the two-stage cam. The bellcrank of this second roller is arranged to actuate three microswitches (described in paragraph 2.31). The follower is spring-loaded to run the first roller (aluminum alloy) on the outermost surface of the drum-wound boom strip, while the second roller (stainless steel) remains poised over the revolving two-stage cam. The two-stage cam provides two 'drops'--the first to slow down rotation; the second to halt it completely. This operation is described in SECTION 3.

DRIVE MECHANISM

2.25 The proposed drive mechanism consists of a 28-volt d.c. motor having an integral gearhead, an external reduction gear, and a microswitch arrangement for electrical control of the system.

Motor

2.26 The motor specifications are as follows:

Type - Globe, 43A571
No-load Speed - 22,000 rpm
Design-load Speed - 13,000 rpm
Brushes - Silver impregnated
Shunt Wound Field - 2 pole
Bearings - Stainless steel, double-shielded ball
Lubricant - GE F50 Silicone oil
Design Voltage - 28-volt d.c.
Design Current - 0.32 amps
No-load Current - 0.26 amps
Continuous Rating - 200 hrs (Space environment)
Planetary Gear Ratio - 733 : 1

2.27 The proposed motor is a modified permanent magnet d.c. type; the permanent magnet is replaced by a shunt wound field to eliminate stray magnetic fields from the motor when not operating. The motor itself is highly reliable within the restrictions of brush types, and power output is adequate for boom rewinding operations. An eight-pin terminal board for the motor control circuit is mounted on the inside and rear of the left-hand sideplate.

2.28 The specified vacuum and temperature requirements are within the capabilities of the proposed silicone lubricated motor. Motors of this type have run for 200 hours at a pressure of 10^{-8} mm Hg without failure. If longer periods of exposure to low pressure were specified, it would still be possible to use these simple prime movers, by supplying a wick and lubricant reservoir to maintain the internal pressure of the motor above that at which cold welding would occur. The time and cycling limitations on these motors are not known; but life expectation is in the order of 500 hours, dependent upon reservoir size.

2.29 More complex motors in the sealed-drive category, and the new brushless type d.c. motors, could be considered if the weight penalties involved were acceptable; however, it is considered that these devices are unnecessary for the present specification.

Gear Assembly

2.30 The drive for the storage drum comprises a spur gear assembly; consisting of a stainless steel pinion on the motor shaft, and an aluminum alloy gear-wheel at the right-hand rim of the drum. The gear ratio is 4 : 1.

Microswitches

2.31 Three microswitches (S1, S2, and S3) are located together on the left-hand sideplate (see Figure 2-6). S2 and S3 perform the same function; being double-banked to introduce a reliability factor. The motor control circuit is shown in Figure 3-1. Microswitch S1 brings a resistor (R1) into series with the armature of the motor; S2 and S3 open the power circuits to stop the motor. The complete operation is described in SECTION 3.

SECTION 3

THEORY OF OPERATION

GENERAL

3.1 The following discussion describes the operation of the unit proposed in this report and covers the sequence of events as they arise during the complete cycling of individual components.

MOTOR

3.2 Operation of the motor circuit is described with reference to Figure 3-1.

3.3 Two independent circuits are provided: the armature (terminals 5 and 6) and the field (terminals 7 and 8). The armature circuit is routed through the normally closed contacts of S1 and S2; the field circuit through the normally closed contacts of S3; and with 28-volt d.c. applied, the motor operates. Under the action of the gear drive, the drum commences to revolve in a counter-clockwise direction, and the boom strip and conductor tapes are paid out.

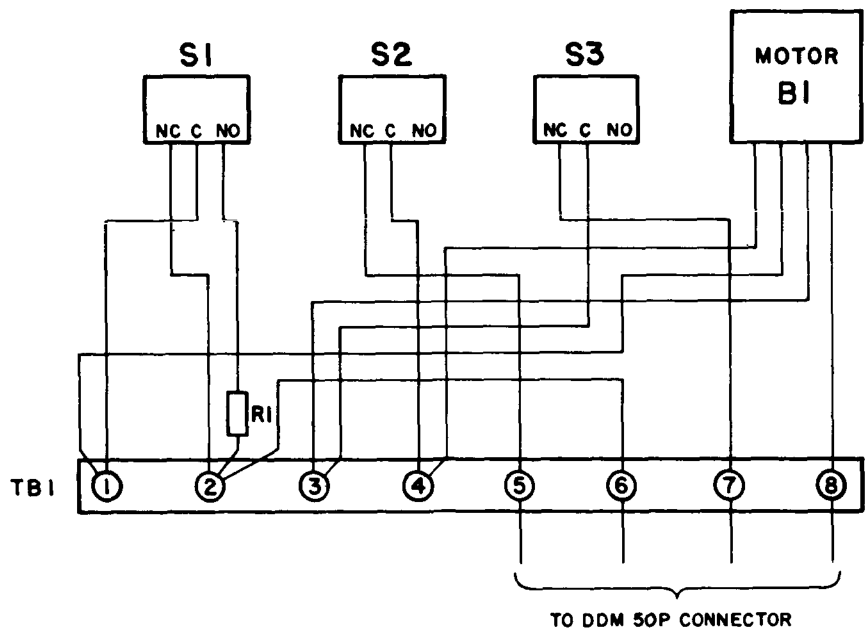

Figure 3-1. Electrical Schematic

BOOM

3.4 The boom strip departs the drum at the radial on the centre-line of the unit, and, on leaving the take-off rollers, the edges of the strip pass between the bearing surfaces of the 'edge' and 'touch' form-rollers.

3.5 The boom is now in transition from strip to tubular configuration. Due to the heat-treat properties, the edges will be endeavouring to curl up and in, and must be restrained and guided if 'oil-canning' and subsequent buckling of the strip are to be avoided. The form rollers are provided for this purpose.

3.6 The next stage in the control of boom configuration occurs in the guide at the exit from the chassis. This guide provides a long arm to take out bending moment loading and minimize the error multiplication of the guidance system (refer to APPENDIX II , paragraph 10, et seqq) and, with the cross section of the boom still in transition at this point, further controls the edges of the strip. The relatively low torsion loads introduced during this stage result in a low torque at the cradle; hence, the freedom to rotate. Repeatability, therefore, is retained, subject to the breakout torque of the bearing.

Extension Velocity

3.7 When properly released, the internal strain energy of a stored boom element can introduce various conditions of self-extension--from the violent, through the neutral, to the slightly back-loaded boom; dependent upon the type of guidance mechanism employed.

3.8 The means of guiding and restraining the boom described in this report permits full use of the self-extension energy of the stored material. An element characteristic results, wherein the strip requires only a small amount of power to commence and maintain boom extension. The handling considerations of both boom and tapes favour a low extension velocity, due to the severity of the loads imposed if slight displacement or erratic behaviour of the strips occurs at high speed; a condition that may result in overstressing and, subsequently, possible jamming of the mechanism. The total extension time, therefore, is in the order of four minutes, at a motor power level of six watts.

CONDUCTOR TAPES

3.9 At the commencement of boom extension, the conductor tapes are as shown in Figure 3-2; with the tapes wound onto the core in the reverse direction to that of the boom, for half the number of required turns of the drum (sixteen and one-half) to fully extend the boom.

3.10 As the drum rotates, the tape exit point peels the tapes off the core and, through the action of the interchange loop, winds them loosely against the outer surface of the interchange chamber. When half the total drum turns have been made, the conductor tapes will be completely unwrapped from the core. During the remainder of the drum turns, the tapes are rewound onto the core in the reverse direction to that of before. An additional half turn of the tapes is provided to prevent tension being applied.

3.11 If the boom is now retracted, the action within the interchange chamber is vice versa to that just described (refer to paragraph 2.16).

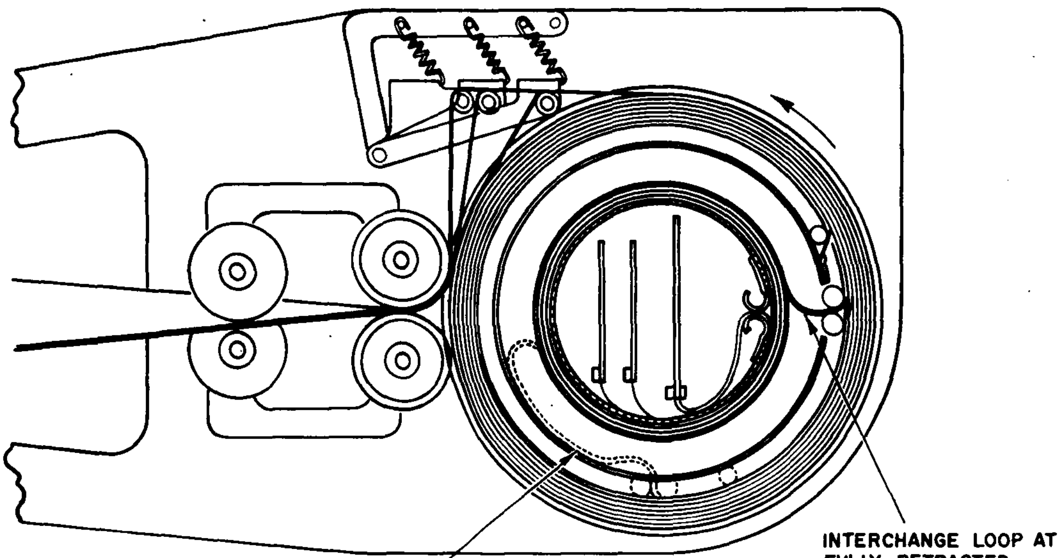

Figure 3-2. Boom and Conductor Tapes at Start of Extension.

TAKE-UP SYSTEM

3.12 As stated in paragraph 2.20, the take-up system compensates for the difference in conductor-tape lengths.

3.13 Where the stored boom strip and conductor tapes become the outside winding on the drum, the next stage, as the boom commences to unfurl, is the 'feed' through the take-off rollers; where the boom strip changes direction, and no longer need the conductor tapes be of greater individual length (refer to paragraph 2.14).

3.14 Due to this difference in length between the individual strips when stored, some means must be provided to compensate for this state while the boom strip is departing from the drum and extending through the take-off rollers. Were no such means provided, each tape--commencing with the uppermost, which is two and one-quarter inches longer than the boom--would set up a backwave against the take-off rollers, and so constitute a tight packing condition; the possible jamming of the feed being a subsequent hazard. However, the take-up system is provided to avoid this contingency.

3.15 The pulleys are spring-loaded to the small gantry assembly, and over each is run an individual conductor tape; the tapes then re-uniting to travel, with the boom strip, through the take-off rollers. As the boom is extending, and the surplus in the conductor tapes is tending to gather, the pulleys will maintain tape tension; so removing the slack and the likelihood of backwave development at the rollers.

POSITIONING

3.16 The repeatability and positioning characteristics of STEM's are more detailed in APPENDIX II. In this Section, the operating theory discusses positioning of the boom with respect to extension length only.

3.17 In SECTION 2 it has already been shown that, when the boom is fully extended, the root clamp is at approximately 180 degrees from the take-off rollers, and that the remaining half of the drum surface is bared--exposing the slot located just inboard of the rim at approximately 320 degrees clockwise. See now Figure 3-2.

3.18 As the boom approaches the limit of extension, the roller of the follower--which until now has been running on the surface of the drum-wound boom strip--drops off the strip, and commences running on the now bared surface of the drum. The drum continues to revolve, and the follower drops through the slot.

3.19 At this stage, the cam has arrived directly under the second follower, the roller of which now runs on the bearing surface. Further rotation of the drum brings the first 'drop' and actuation of microswitch S1. The normally closed circuit of S1 is opened; the normally open circuit is now closed; resistor R1 is brought into series with the motor armature, and reduces the motor rpm to approximately half the 'under-load' value.

3.20 At the second 'drop' in the cam, microswitches S2 and S3 are actuated simultaneously; the normally closed contacts are opened, and power is removed entirely from the motor circuits. In addition to providing for the actuation of S2 and S3, this second 'drop' becomes a detent, and physically arrests further rotation of the drum. Total extension errors result only from variations in boom length; due to temperature and stress, and errors in physically positioning the drum.

BOOM STORING

3.21 For ground retraction purposes, the motor may be employed; by reversing the polarity across the armature, and by physically lifting the follower until the first turn of the drum covers the slot; after which the follower may be permitted to run upon the surface of the boom strip. When the boom is fully retracted, the power can be removed; the high gear ratio of the drive will maintain the unit in the 'stowed' condition.

SECTION 4

ENVIRONMENTAL FACTORS

GENERAL

4.1 The boom unit will be called upon to operate in a rigorous environment, and, in the design of a development model, this factor would be taken into consideration.

MATERIALS

4.2 By means of metal surface treatment, or by substitution of the metal parts by such spaceworthy materials as melamine, fibre-glass, nylon, Teflon, and Mylar, metal-to-metal moving surfaces will be protected or eliminated wherever possible.

4.3 For reasons of economy in power, and a minimum of play at the moving surfaces, the boom system employs a great number of bearings in the guide and drive mechanisms.

4.4 Tests performed on the motor have shown a double-shielded bearing that has a supply of low vapour-pressure silicon oil to have a space environment life in the order of two hundred hours minimum. Therefore, the use of this type of bearing would satisfy the specification requirement; however, a rather slim safety factor would exist.

4.5 A contract for hardware should provide for development, whereby: these bearings can be replaced by adequately tested bushings having non-metallic contact surfaces; and, where necessary, the replacement of the metal balls in the bearings by artificial sapphire, or some other crystaline substance not prone to a vacuum weld to steel. The employment of such bearing materials is more than feasible; in fact, their use if already reduced to commercial practice. It is synonymous, therefore, that a program of this magnitude would require, in this respect, only a small amount of extra funding to enhance the space reliability.

SECTION 5

WEIGHT ESTIMATE

TABLE OF WEIGHTS

5.1 Figure 5-1 is a table of estimated weights for the proposed boom system.

ITEM	VOLUME OR LENGTH OR NUMBER	DENSITY lb/cu in.	ESTIMATED WEIGHT (lb).
Boom	21.0 + 1.5 ft	0.0716	1.60
Conductors	21 + 0.60 x 21 + 1.5 ft 21 + 0.60 x 21 + 1.5 ft 21 + 0.60 x 21 + 1.5 ft	0.0168) 0.0168) 0.0404)	2.60
Connectors	6 off		0.25
Terminal Boards and Wiring	Satellite End		0.15
Motor	Globe 49A		0.42
Storage Drum	6.85 cu in.	0.100	0.50
Central Core	9.38 cu in.	0.100	0.75
Guidance	9.21 cu in.	0.100	0.75
Bearings	1 @ 0.22 + 2 @ 0.25 + 15 @ 0.01 (lbs)		0.85
Take-up System	3.2 cu in.	0.100	0.25
Forward Connector Panel	6.25 cu in.	0.100	0.38
Forward Plug	2.0 cu in.	0.100	0.15
Sideplates	166 sq in. @ 0.125 in.	0.100	1.20
Misc	0.6 cu in.	0.100	0.04
			9.89
Total Weight (including Contingency)			11.00

Figure 5-1. Estimated Weights.

FIGURE OF MERIT

5.2 The estimated weight of the unit is 11.0 lb, of which 2.60 lb is contributed by the conductors themselves.

5.3 These weights should be compared with the weight of cabling alone required under the specification. The total length of No. 22 gauge wire required is (21 + 2) feet times 37 conductors - equalling 850 feet, and of Microdot (21 + 2) feet times 10 conductors - equalling 230 feet. Therefore, using their respective linear densities, the result is -

No. 22 wire - 850 x 0.0035 =	2.98 lb
Microdot - 230 x 0.0110 =	2.53 lb
	5.51 lb

5.4 It is important to note that the total weight of the proposed unit is only twice that of the cabling alone as originally specified.

SECTION 6

CONCLUSION

GENERAL

6.1 As stated earlier in this report, the design features of the unit proposed herein are the progeny of a previously developed system--the A-26 Extendible Boom Unit. In turn, those of the A-26 were born of other designs and principles of a simple nature and of proven reliability, and the information contained in APPENDIX II serves to support this statement.

BOOM LENGTH

6.2 With respect to boom length, no difficulty is foreseen in meeting the specification requirements. The methods of anchoring the boom to the drum and of arresting drum rotation preclude the possibilities of overshooting and undershooting. This feature is described under paragraph 3.16.

BOOM CONSTRUCTION

6.3 The only suitable non-magnetic material available for the boom element at present is beryllium copper. An alternative material--titanium alloy--could later be considered, if and when existing development tests show satisfactory results.

DESIGN ADVANTAGES

6.4 A comparison is drawn between the de Havilland product and one representative type of other extendible boom systems that are under development for spacecraft application; namely, a sectional interlocking tube unit. This type, for example, suffers from a number of severe drawbacks; as follows:

(a) Motive Power -
A high energy is required for reliable operation, and only high-pressure gas from explosive squibs or bottles is suitable for supplying this force. Both these propellants introduce unreliability from factors such as high-pressure sealing and erratic reaction by an explosive charge to a widely varying temperature environment.

(b) Weight -
The tubes and joints must be sturdily constructed, if they are to withstand the high pressures and the shock from abrupt deceleration--resulting from the means of ensuring complete locking of all sections.

(c) Disturbing Forces -
On completion of extension, this deceleration imparts impulsive shocks to the

carrier-vehicle and the instrumentation at the extremity of the boom.

(d) Positional Repeatability -
This factor must suffer, due to the repeated testing of the same boom being a practical impossibility. For instance, such devices are primarily of the 'one shot' type, and, should a reloading or recharging test rig facility be devised, the hand collapsing between shots may quite easily damage delicate seals or carefully matched joints. Moreover, a very difficult mechanical problem is the guarantee that the individual sections will not rotate during rapid extension.

(e) Package Size -
It is unlikely that a relatively reliable boom of this type could give a stacking factor of better than 6 or 7 : 1 (ratio of extended to stored length). A 21-foot stored boom alone, therefore, would be some 30 inches minimum in length.

(f) Electrical Circuitry -
It is fairly obvious that the collapsable tube system must convey the cabling externally, and this feature would necessarily dictate the provision of adequate shielding from the effects of radio 'noise', micro-meteoroid collision, ultra-violet and similar types of radiation.

6.5 On the other hand, the advantages offered by the de Havilland proposed boom system are found in the one-piece construction of the element (providing, thereby, a continuous and, therefore, simple extension cycle), and the compact stowage arrangement of the boom strip and conductor tapes; features that are attainable only through the medium of the flat strip and storage drum principle. In comparison with the dimensions of a stored sectional tube (refer to paragraph 6.4 (e)), the complete system assembly is only a little over 23 inches long and, for no increase in length and only about 2 lb. increase in weight, could easily accommodate a 40-foot boom if required, complete with electrical circuitry. The fact that the boom will almost self-extend, requiring only a small drive-motor, is in itself considerably noteworthy.

6.6 For test purposes, the boom can be extended and retracted repeatedly (through more than 100 cycles) with no loss in calibration or performance; for example, to satisfy other customer specifications in the past, a retraction feature has been incorporated by merely the addition of a simple circuit and switching to the drive motor.

6.7 As already shown earlier in this report, shielding of the electrical circuits is provided by the boom and, consequently, no extra weight is introduced thereto.

6.8 Similar techniques to that of STEM design could be adopted by other manufacturing concerns; but none would possess the three-year background of research and development in these devices that exists at de Havilland.

REPEATABILITY

6.9 The positioning errors of boom elements are discussed in APPENDIX II. It will be seen that these errors can be largely predetermined from tests, and, as a result of which, their values may well be brought to within, or the threshold of, the specified tolerances. This task is difficult, to say the least, due to the intricacies and inaccuracies attendant to reproducing a zero 'g' environment on earth. It is also shown how this condition is simulated for test purposes.

CABLING

6.10 As described in SECTION 2, a departure from the specification is proposed with respect to the cabling employed. Although a system could be designed that employed the specified type of cabling, the result would be impracticable from the standpoint of unit dimensions and weight. Moreover, the handling of grouped leads would occasion complication in design and system operation. Furthermore, not only do the Mylar strip conduits dispense with these last two problems, they also provide five conductors over and above the total number specified. Additionally, and with particular emphasis on the gross weight of the complete boom system, the Mylar conduits contribute toward a considerable saving in this respect; as shown in the following paragraphs.

WEIGHT

6.11 From SECTION 5, it will be seen that the total weight of the proposed conductor tapes is less than half the total weight of the cabling called for in the specification. By employing this type of conduit, the design team were thus able to simplify the form of the storage, drive, and guidance mechanisms; thereby retaining a structure of light weight.

6.12 Had the specified cabling been adopted, the design features would have become complicated, enlarged, and, so, somewhat weighty--resulting in an estimated gross weight in the order of 18.0 lb minimum. However, the alternative is proposed and results in an estimated gross weight of only 11.0 lb.

REFINEMENTS BY DEVELOPMENT

6.13 If a development program were instituted wherein prototypes are first constructed to drawing, followed by modification after testing, the following results should be achieved.

Weight

6.14 The mechanical design would be simplified and should show a subsequent reduction in overall weight. Further weight-saving would be attained by utilizing fibre-glass or other non-metallics in the main structure; in particular, the use of a titanium alloy boom would show a saving of approximately one-half pound.

Wiring

6.15 A development program would effect a considerable improvement in the wiring system. For example: the number of junctures per conductor could be reduced; the most advanced and reliable connectors could be utilized; where possible, welded connections would be substituted for those now soldered.

RELIABILITY

6.16 The design of the proposed boom system employs the basic techniques of other proven designs. Although new ideas have been applied, alternative materials proposed, and some modification incorporated, de Havilland are confident that, after suitable testing, a thoroughly reliable extendible boom system for space-vehicles can be produced.

APPENDIX I

GODDARD SPACE FLIGHT CENTER

SPECIFICATIONS FOR DEVELOPMENT
OF
BOOM ERECTION SYSTEM

APPENDIX II

HISTORY AND DESIGN ANALYSIS
OF
STORED - TUBULAR - EXTENDIBLE - MEMBER
DEVICES

APPENDIX I

GODDARD SPACE FLIGHT CENTER

SPECIFICATIONS FOR DEVELOPMENT OF BOOM ERECTION SYSTEM

I. Purpose

The purpose of this task is to study design approaches and recommend the most practical and feasible to pursue based on requirements. This design should incorporate the folding tubular tape principle which has been developed by the de Havilland Aircraft of Canada, Limited.

II. Requirements

Utilizing the basic concept of the folding tape system, disclose a design that will meet the following requirements.

A. Length of Boom:

Extended length should be twenty-one feet plus or minus 0.030 inches.

B. Material:

All boom material must be non-magnetic.

C. Repeatable Positional Accuracy:

Outer end of boom must be on axis to within a $1/4^{\circ}$ half angle cone and torsionally repeatable to within $\pm 1/4^{\circ}$.

D. Cabling:

Extended along the full length inside the boom will be a cable pack made up of thirty-seven (37) No. 22 wires and ten (10) micro-dot leads.

E. Loading:

Secured to the outermost tip of the boom will be a non-collapsible seventy-two (72) inch tubular section which supports magnetometer components as outlined on SK 708. The boom must be capable of supporting the extended components only in a 0-g condition. However, as stated in paragraph II-H, the boom will be extended for testing on earth.

F. Weight:

The weight of the complete extension system should be the minimum required to maintain the structural integrity of the assembly.

G. Retraction:

Retraction is not required in space and should be manual on the ground.

H. Ground Test:

When an appropriate support structure is used, the boom must be capable of accurately extending the magnetometer components and cabling while in a 1-g field. The support structure will be supplied by GSFC.

III For the purposes of this study the following environmental test conditions should be used in the design phase of the investigation. In the non-extended position the complete boom system will undergo the following environmental tests which represent either boost phase during launch or orbital conditions.

Acceleration

The acceleration level will be 13 g's in three mutually perpendicular directions.

Vibration

Sinusoidal

Sinusoidal sweep is typical for each of three orthogonal axes.

Frequency Range cps	g-rms	Sweep Rate (log)
5 - 250	3.5	1/2 octave/minute
250 - 400	6.5	" " "
400 - 3000	13.0	" " "

Random

Random motion applies to three orthogonal axes.

Frequency Range cps	Power Spectral Density (g^2/cps)	Time (min) Each axis
20 - 2000	0.10	12.0

Shock

Wave shape	1/2 sine wave
Each axis	30 g's
Time	6 milliseconds

Thermal Vacuum

In addition the system must be capable of functioning under the following conditions which represent orbital flight.

Hot Thermal Vacuum

Pressure:	1×10^{-5} mm of Hg.
Temperature:	$45^{o}C$
Time:	24 hours

Cold Thermal Vacuum

Pressure:	1×10^{-5} mm of Hg.
Temperature:	$-5^{o}C$
Time:	24 hours

Et seqq. omitted - Ed.

APPENDIX II

HISTORY AND DESIGN ANALYSIS OF STORED-TUBULAR-EXTENDIBLE-MEMBER DEVICES

INTRODUCTION

1. Stored-Tubular-Extendible-Members (STEM's) are a design development by de Havilland Aircraft of Canada Ltd. In brief, these units provide a highly satisfactory means of packaging lengthy antenna or boom elements in carrier-vehicles having a limited stowage capacity, and in which there exists a requirement for both the extension and retraction of the element. The following is a synopsis of the design, production processing, and performance of these units, and is provided to facilitate the assessment of the de Havilland capability in this respect.

2. The original basis for the STEM design was a technique investigated by the National Research Council of Canada. The technique was further developed by the Canadian Army Development Establishment and later, in conjunction, by the Canadian Defence Research Telecommunications Establishment and de Havilland. During recent years, the unique features of STEM design have been the subject of application for patent rights.

3. The STEM principle has already been applied to equipment now being operated. In particular, these units have performed successfully on space vehicles. In 1959, the Special Products & Applied Research Division of de Havilland Aircraft of Canada undertook the design and development program that produced the antennas for Canada's Topside Sounder Satellite.

4. Many STEM devices have been produced over the period of their development by the Company; the operation and reliability of these units has been proven repeatedly--both in test programs and practical application. Many problems have arisen and been dealt with effectively. No new idea or material is incorporated in a boom or antenna system, until it has first been subjected to a sound theoretical study and a thorough development schedule. Figures 9 and 10 are photographs of one successful development--designated the A-26 Boom Unit.

THE STEM PRINCIPLE

5 The STEM principle is depicted in its basic form in Figure 1. The boom element is formed out of strip material. The strip is heat-treated into a circular section, in such a manner that the edges of the material overlap to a specific degree, dependent upon requirement (see Figure 2). This overlap, when in the order of 180 degrees, provides the tubular element with a strength almost equivalent to that of a seamless tube of the same diameter and wall thickness. When retracted, the boom element is stored in the strained and flattened condition by winding it externally onto a drum or internally into a cassette;

it is continuously transformed into the flattened condition by passing it through a suitable guidance system.

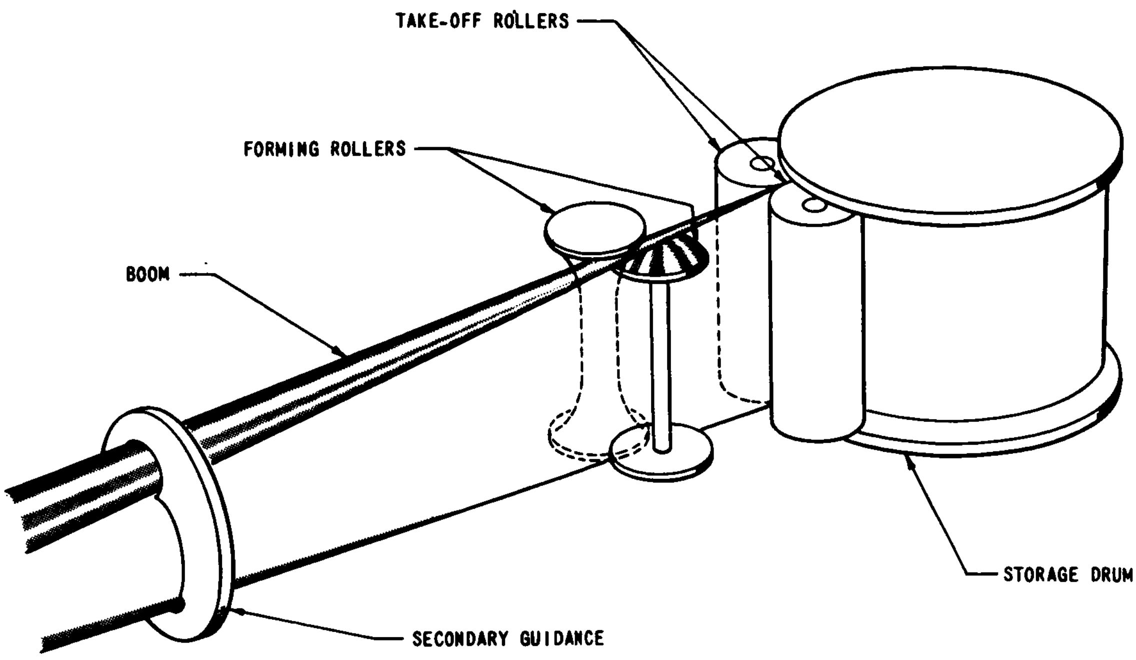

Figure 1. The 'STEM' Principle.

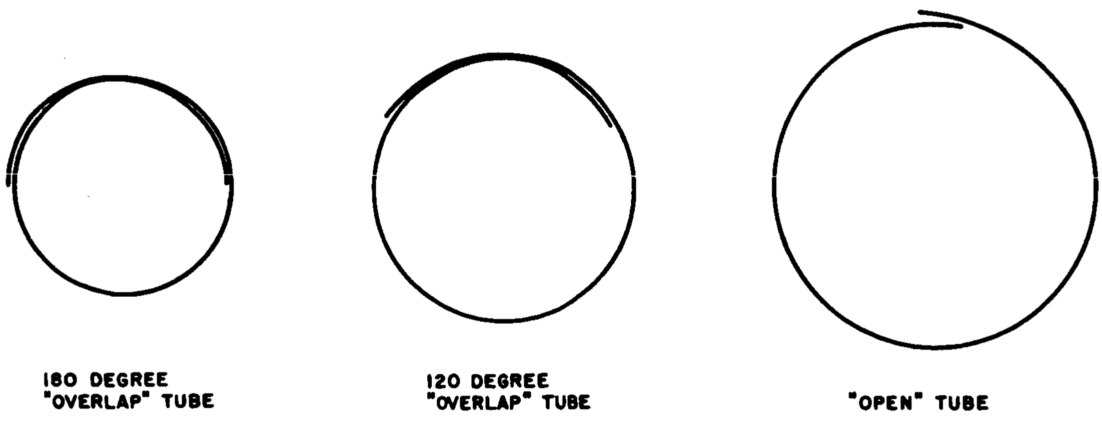

Figure 2. Cross Section of Typical Tubes.

6. It will be appreciated that the process of flattening and coiling the boom element imparts a strain energy to the material; resulting in the element having an inherent tendency to resume tubular configuration where it departs the drum, so promoting an inclination to self-extend. The stage of transformation, from the flat to the tubular, is termed 'the area of ploy'.

7. Dependent upon the particular requirement, the guidance and drive mechanisms are so arranged to control the reaction of the boom element--from a condition in which the element will completely self-extend, to a condition where a small motor is used to commence and maintain extension.

8. Where a boom is to be subjected to bending moments from wind, weight, inertia or despin loading, it is possible to increase the bending strength of the boom by nesting several identical elements together, or by increasing element diameter and thickness.

9. The boom has already been described as formed into a circular section of--in some cases--180 degrees overlap, and while providing a boom of high root buckling strength, the technique involves a section of overlapped element in close contact. Where torsional and positional repeatability is a design requirement, the randomly friction-loaded area along the length of the overlap introduces non-repeatable variations in boom shape and tip torsional orientation. For this reason, booms with close positional tolerance requirements are usually of an 'open' design. A boom is referred to as 'open', even when some overlap is provided to exclude direct external radiation; but, in this case, the overlapped sections do not come into contact with each other.

REPEATABILITY

Position Errors - Random and Repeatable

10. Due to the nature of the material used in the element, small loads and distortion will assume major importance in the final boom shape. The element is little thicker than paper and, in the open configuration, has a torsional rigidity in the order of one ten-thousandth of that of a thin-walled tube having the same wall thickness and diameter. Load propogation develops shear along the four free edges of the element, and any distortion enforced on these edges will produce large changes in shape and a twist at the end of the boom. These changes in the shape, from the natural contour, can be broken down into the repeatable and random variations, or shape errors; the repeatable errors being of little significance to end accuracy provided they are known.

Repeatable Errors

11. Broadly speaking, the natural lengthwise shape of a fully formed, unsupported, and unloaded element is straight, within given tolerances (nominally $\pm$ 1.0 inch over a 20-foot length). The non-linearities are largely a function of the deviations in edge alignment, material uniformity, and heat-treat uniformity, and are repeatable within the fatigue and relaxation limits of the treated material.

12. When mounted in the boom unit, the element is then subjected to a collection of additional factors which tend to distort the natural shape. Where the element departs the take-off roller, it begins to 'ploy', and introduces a curvature in the shape with respect to the axis through the guidance mechanism. In turn, the guidance mechanism invariably distorts the natural 'ploy' shape; but, assuming the action of the guidance mechanism to be constant, then this effect may be considered repeatable. The curvature in the element disappears a few feet out from the unit, leaving an offset and angular change in direction relative to the axis through the guidance mechanism. This change in direction is repeatable; therefore, the factor may be pre-determined, and an

allowance made when establishing the attitude of the boom unit mounting in the carrier-vehicle.

13. Another cause of deviation from the natural shape is found in the shear distortions that are fed in by the element edge guides. Additionally, the boom is clamped at both ends and possesses small internal loads introduced by the screws and thrust faces employed. It is obvious, therefore, that because of the multiplication effect of shear loads, any small distortion of short segments will produce large distortions of the total boom. For example, it is possible for a 0.001-inch misalignment at the end plug to result in a 5.5-degree twist at the tip, relative to the base. However, these errors are repeatable, if the input distortions are constant.

Non-Repeatable Errors

14. Non-repeatable errors are due almost entirely to tolerance problems in the guidance of the boom.

15. The random friction encountered in the overlapped cross section of the normal element will introduce a random error that is dependent upon the loading and speed history of the extension.

16. Another variable loading, that is independent of the effects of boom guidance, is the random load originated by a cable pack during extension and by the relaxation of any tension or loading induced by the extension process.

17. From the foregoing statements, it can be said that the greatest problem regarding repeatability lies in the play produced by tolerance build-ups. Any small shift created by running slack, or other play, can result in a much multiplied error in the final configuration. Mainly, the solution to this problem is one of producing simple, accurate, high-quality equipment.

Element Material Hysteresis

18. In these booms, material hysteresis is not a measurable error because the material is being worked below the elastic limit, and repeated cycling of stress does not tend to produce permanent distortions in the boom.

19. By experiment, it has also been found that, after being stored in the fully strained condition for extended periods, a boom will show very little change in size or shape. For instance, after being stored on a three-quarter inch mandrel for two years, a one-half inch diameter boom of beryllium copper showed an increase in diameter of only 0.005 inch.

Environmental Non-linearities

20. A problem that becomes more important as boom length is increased, is the input of external loads such as changes in satellite orientation in orbit, and thermal distortion due to solar radiation.

21. For example, because of the relatively high moment of inertia of an extended

boom, any change in satellite rotation may produce large bending moments at the root of the boom. A very important investigation, therefore, is an analysis of the satellite rotational speed, when the boom is first extended, and any subsequent change in satellite motion. The fact that a locally crippled boom will usually re-extend is of little consequence, when a tolerance has been placed on the boom tip position.

22. Moreover, when the boom is extended from a satellite that is stabilized in some manner to seek the earth, the boom will receive varying amounts of solar radiation from a constantly changing direction. As the sun warms one side of the boom, a thermal gradient is set up to balance the heat flux through the tube. This thermal gradient causes the element material to expand or contract locally, introducing a measureable distortion into the boom natural shape. The non-symmetrical nature of the tube cross section will make these distortions unpredictable if a plane of symmetry is not oriented exactly to the direction of radiation.

THE DATUM

23. Repeatability has no meaning without a datum or mean line, and, in the case of systems designed for use in space, it is difficult to simulate on earth the zero 'g' and vacuum conditions under which the system will eventually operate. However, the Special Products and Applied Research Division of de Havilland has spent considerable time and effort in the study of mechanisms that will approximate these factors.

24. Originally, booms were extended on small floats in a large water tank. This practice alone gives a zero restraint condition in the horizontal plane, if the floats do not approach the sides of the tank where surface tension effects are measurable. When tests are done in two orthogonal planes, a first approximation to the antenna shape can be made. It can be appreciated, however, that if the antenna possesses a natural curvature in the vertical plane, the system of floats will restrain the shape unnaturally in this plane. This unnatural restraint affects the shape in the orthogonal plane, because of the low torsional stiffness of the boom. Therefore, whereas the restraint in the horizontal plane is of a very low value, the restraint in the vertical and torsional planes is inadequate with this system.

25. Ideally, the restraint in the vertical plane should apply a distributed constant force of minus one-'g' to the boom, for any deflection. In reality, the provision of such a distributed force would be a practical impossibility, and, in lieu, a system of discrete supports at approximately five-foot intervals was introduced. These supports comprise a flexible string hung over a large diameter pulley of low breakout friction. A counter-weight to a five-foot segment of boom is attached to one end of the string; a boom support hoop to the other; thus, only minimal restraint to the natural shape of the boom in the vertical plane will be applied. If the support hoop is hung in a bearing, the boom will be free to rotate.

26. In summary, there are floats to provide horizontal freedom, a system of counterbalances to support the boom freely in the vertical plane, and a rotatable support to provide torsional freedom. A series of readings must be taken to provide a picture of the remaining restraint from breakout friction. From the median of these points, an accurate picture of the true boom shape can be drawn.

Repeatability Tests

27. Tests carried out on two booms have shown repeatability to be of a high order.

28. A simple float support system was employed to test a one-half inch diameter boom of beryllium copper. The purpose was to determine positional, but not torsional, error. Over eight extensions, the total position error spread was three-eighths of an inch at 30 feet, or approximately plus or minus 3 minutes of arc.

29. A slightly more sophisticated system was employed in the tests of an A-26 boom (see Figures 9 and 10). On an average of 50 points, the positional standard deviation was approximately plus or minus one-eighth of an inch at 20 feet; the torsional standard deviation was approximately plus or minus one and one-half degrees.

MATERIALS AND MATERIAL PROPERTIES

30. The particular requirements of STEM elements eliminate many of the commonly used high-strength materials. Some materials worthy of investigation are beryllium copper, certain high carbon steels, the 300-series stainless steels, and certain titanium alloys. Of the above families, only two are totally non-magnetic. The high carbon steels are very magnetic, and the 300-series of stainless steels have magnetic properties that increase with increasing mechanical strength. Neither beryllium copper nor titanium alloy are magnetic; therefore, both would be satisfactory materials for magnetometer boom elements.

31. At the present time beryllium copper is the only proven element material. The use of titanium alloy is under investigation; this material could be a possible choice for a second-generation boom system. A table of critical properties of boom material is provided in Figure 3. The following section describing performance will indicate those material properties which are of importance in boom design.

	MATERIAL			
	Beryllium Copper	A Typical High Carbon Steel	Typical Stainless	Titanium Alloy
Yield Strength (1000 psi)	190	190	320	210
E Transverse (psi x 10^{-6})	19	30	35.6	16
E Long (psi x 10^{-6})	19	30	39.2	16
μ Poisson Ratio	0.30	0.33	0.33	0.304
Electrical Conductivity (% Annealed Cu)	16%	7.2%	2.4%	2.1%

Figure 3. Critical Properties of Boom Material. (Continued overleaf)

Figure 3. (cont'd)

MATERIAL

	Beryllium Copper	A Typical High Carbon Steel	Typical Stainless	Titanium Alloy
Thermal Conductivity (BTU/hr ft °F)	44	10 (approx)	9 @ 70°F 12 @ 500°F	4 @ 70°F 8.2 @ 400°F
Corrosion Resistance	very good	poor	good	very good
Magnetic Properties	none	high	slight	none
Density (LB/IN^3)	.298	.286	.286	.175

Figure 3. Critical Properties of Boom Material.

PERFORMANCE

Glossary of Performance Values

A = Area of payload

B = Constant

Cd_b = Drag coefficient of boom

Cd_p = Drag coefficient of payload

D = Boom diameter

E_L = Young's modulus in a longitudinal direction

E_T = Young's modulus tangential to direction of rolling

F_y = Yield stress

g = Acceleration of gravity

I_o = Polar moment of inertia of satellite with booms retracted

k = Overlap factor $= 1 + \dfrac{\phi}{360^{\circ}}$

(Continued overleaf)

Glossary of Performance Values (cont'd)

K	=	Emperical constant
L	=	Boom length
m	=	Mass = W/g
M_b	=	Bending moment
M_p	=	Mass of payload
R	=	Distance of boom root from centre of rotation
t	=	Strip thickness
v	=	Boom extension velocity
V	=	Wind velocity
W	=	Strip width
W_b	=	Boom weight
W_p	=	Payload weight
W_s	=	Boom weight/linear foot
x	=	Distance from boom root to element
α	=	Angular acceleration
γ	=	Overlap fit constant
θ	=	Tilt angle from normal
μ	=	Poisson's ratio
ρ_a	=	Air density - mass/cu lb.
ρ_b	=	Boom material density - mass/cu ft.
ρ_s	=	Boom density - mass/linear foot
ϕ	=	Angle of boom overlap - degrees
ω	=	Angular velocity

APPLIED LOADING

32. The following are the four common loads applied to booms or antennas. Since

failure is usually due to buckling, the loads will be expressed as root bending moments.

(a) TILT LOADS

$$M_b = L W_p \sin\theta + \rho_b g L^2 t W \sin\theta$$
$$= L m_p (g \sin\theta) + \frac{\rho_b}{2} . L^2 . t . W . (g \sin\theta)$$

(b) ANGULAR ACCELERATION LOADS

$$M_b = m_p \alpha L (L + R) + \alpha \rho_s L^2 \left(\frac{L}{3} + \frac{R}{2}\right)$$

(c) WIND LOADS

$$M_b = \frac{\rho_a}{2} V^2 \left(C d_b d L^2 + C d_p A L\right)$$

(d) DESPIN LOADS - No Payload

$$M_b = - B . \rho_s^{1/2} . v . I_o^{2/3} \text{ at } L = \left(\frac{3}{8} \frac{I_o}{\rho_s}\right)^{1/3}$$

where	B = 0.367	n = 2
	B = 0.231	n = 4
	B = 0.173	n = 6
	B = 0.146	n = 8

ALLOWABLE BENDING MOMENT

33. This stress analysis of the allowable boom bending moment will assume that the following formula is true if K is experimentally determined for a particular geometry:

$$M_b = \frac{K E_L D t^2}{2(1 - \mu^2)}$$

or for n tubes with overlap

$$M_b = \frac{K E_L D t^2 n^\gamma}{2(1 - \mu^2)}$$

where γ is another experimental factor depending on overlap.

The diameter to which the strip material can be bent or the diameter from which it can be straightened, follows the flexure formula:

$$\frac{D}{t} = \frac{E_T}{F_{max}}$$

where F_{max} = the maximum allowable stress = $\frac{2}{3} F_y$

Thus $$M_b = \frac{K E_L E_T}{2 F_{max} (1-\mu^2)} \cdot t^2$$

$$= \frac{2K}{q} \cdot \frac{E_L}{E_T^2} \cdot \frac{F_y}{(1-\mu^2)} \cdot D^3$$

It is to be noted that the value of K in the above formula varies with the angle from the 'open' segment.

BOOM OPTIMIZATION

34. If minimum weight for a given boom strength is a design requirement we may rearrange the formula using $W = k \pi D$. The weight per foot of an element is given by:

$$W_s = \rho_b W t g$$

$$= \rho_b g k \pi D t$$

$$= \rho_b g k \pi D \cdot \frac{2}{3} \frac{F_y}{E_T}$$

$$\therefore W_s = \frac{2\pi g}{3} \cdot k \cdot \frac{F_y}{E_T} \cdot \rho_b \cdot D^2$$

thus

$$\frac{W_s}{M_b} = \frac{2\pi g}{3} \cdot k \cdot \frac{F_y}{E_T} \cdot \rho_b \cdot D^2 \times \frac{q}{2K} \cdot \frac{E_T^2}{E_L} \cdot \frac{(1-\mu^2)}{F_y^2} \cdot \frac{1}{D^3}$$

$$\frac{W_s}{M_b} = 3\pi g \cdot \frac{k}{K} \cdot \frac{E_T}{E_L} \cdot \frac{\rho_b \cdot (1-\mu^2)}{F_y \cdot D}$$

The optimum boom will have a large yield strength, the maximum practical diameter and the minimum overlap to strength ratio possible.

GRAPHS

35. Figures 4 to 8 are presented as an introduction to the strength capabilities of STEM devices. Strip width is used as a reference for the first four curves, since it determines the basic size of the boom unit. The assumptions and limitations used in presenting these figures are as follows:

(a) FIGURE 4 - TUBE DIAMETER vs STRIP WIDTH
The variable for this figure is the tube overlap in degrees. Strip thickness is such as material properties will allow.

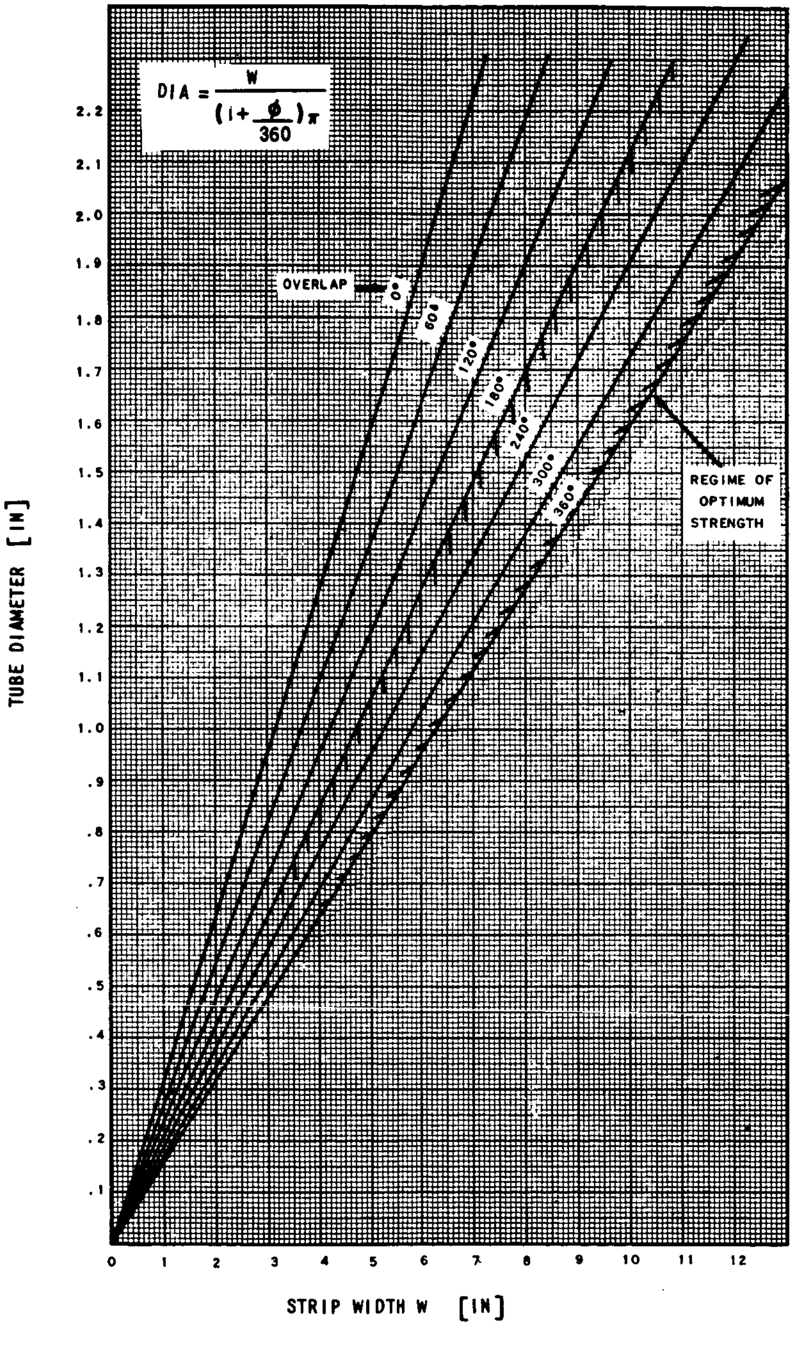

Figure 4. Tube Diameter vs Strip Width.

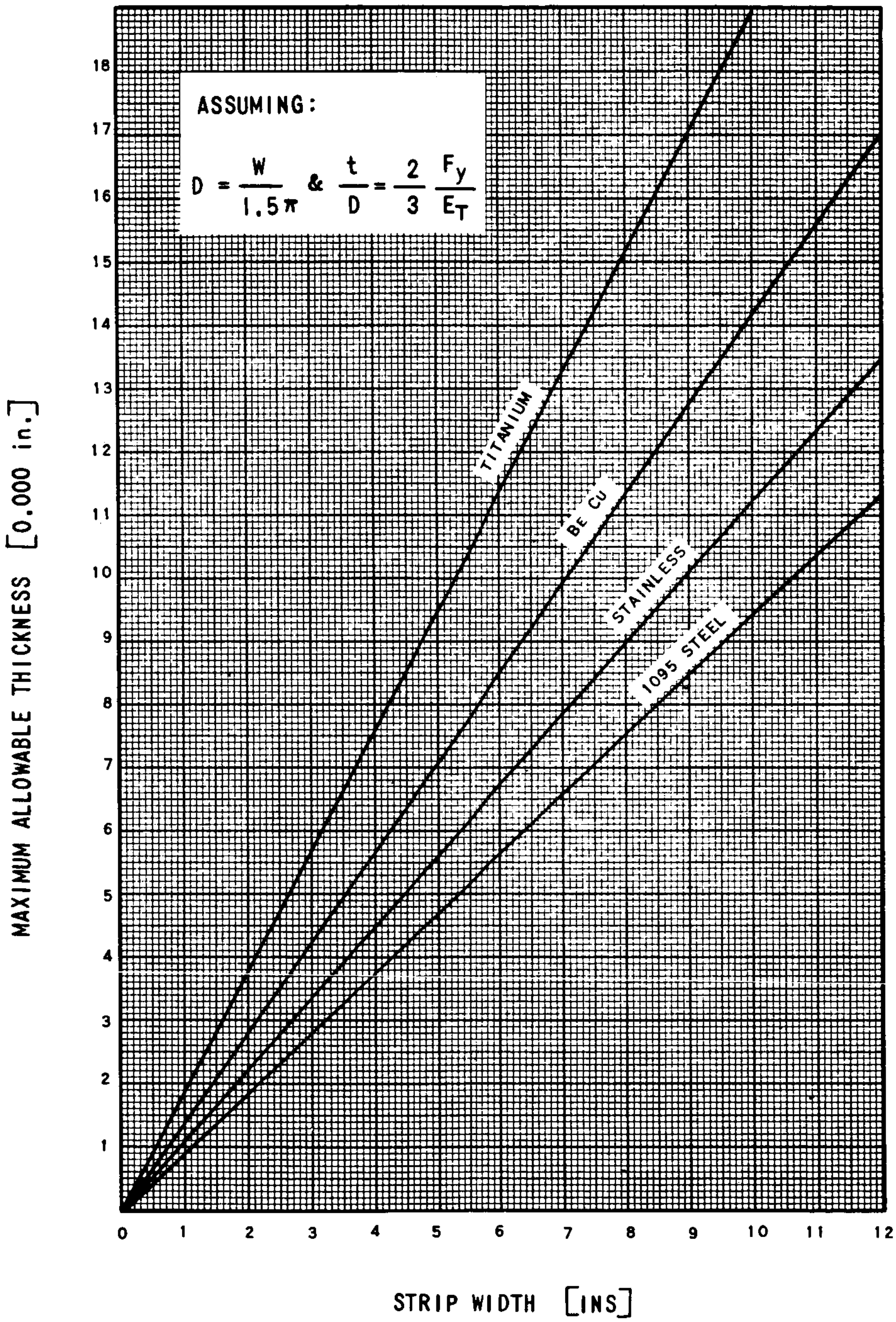

Figure 5. Maximum Strip Thickness vs Strip Width.

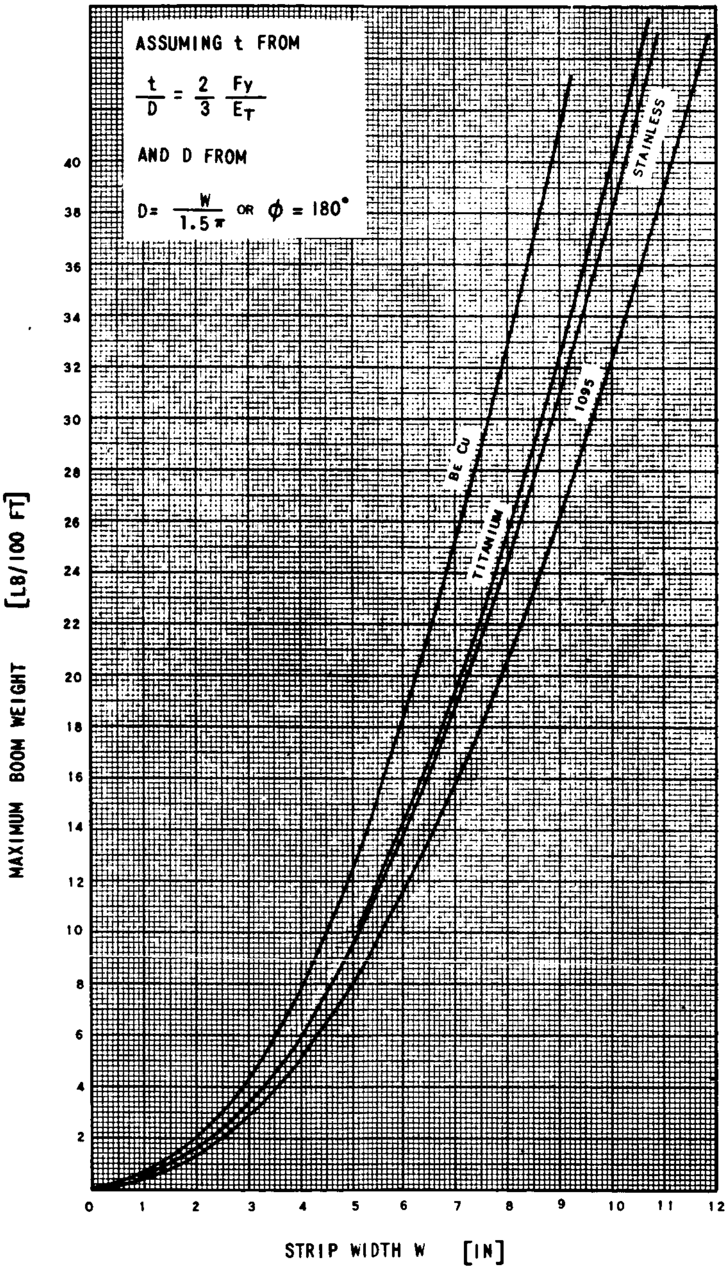

Figure 6. Boom Weight vs Strip Width.

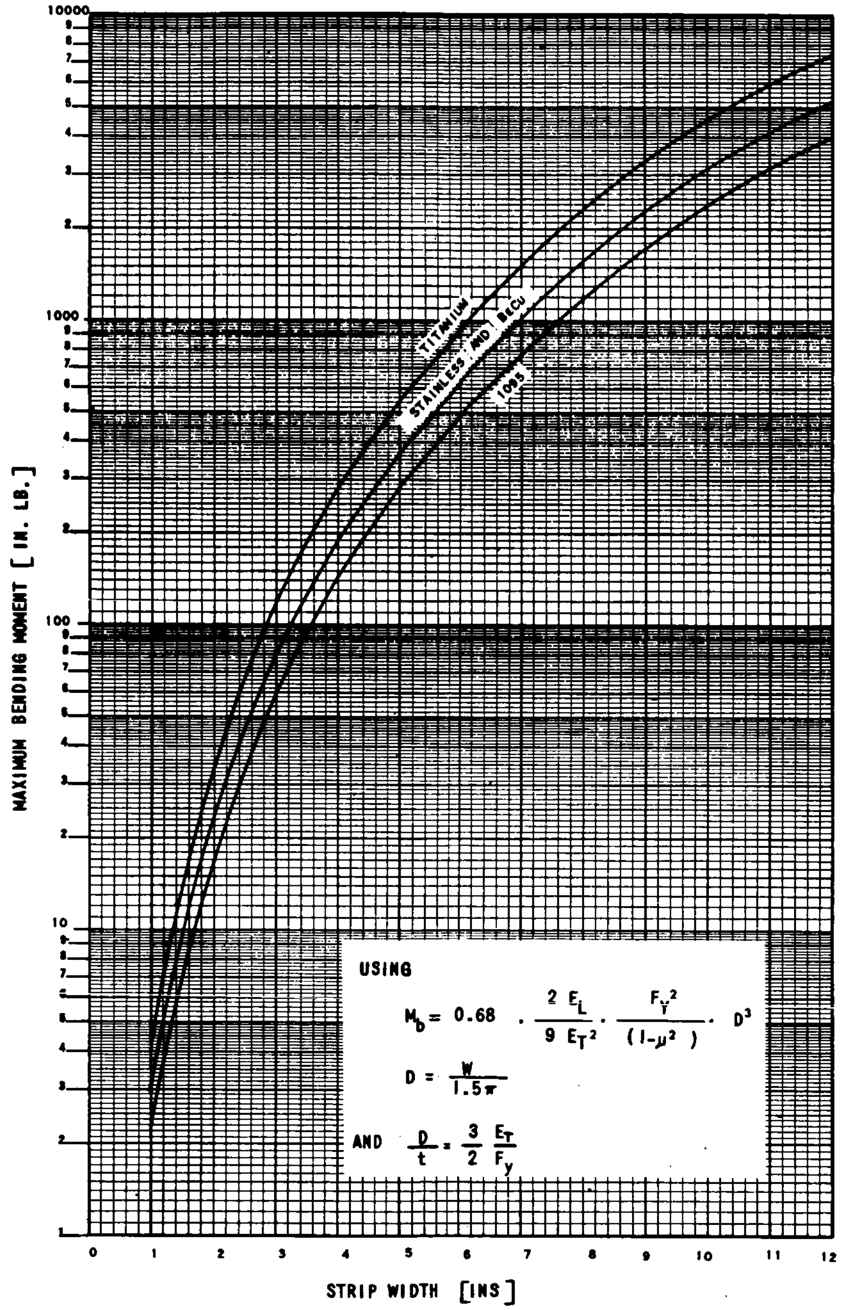

Figure 7. Maximum Bending Moment vs Strip Width.

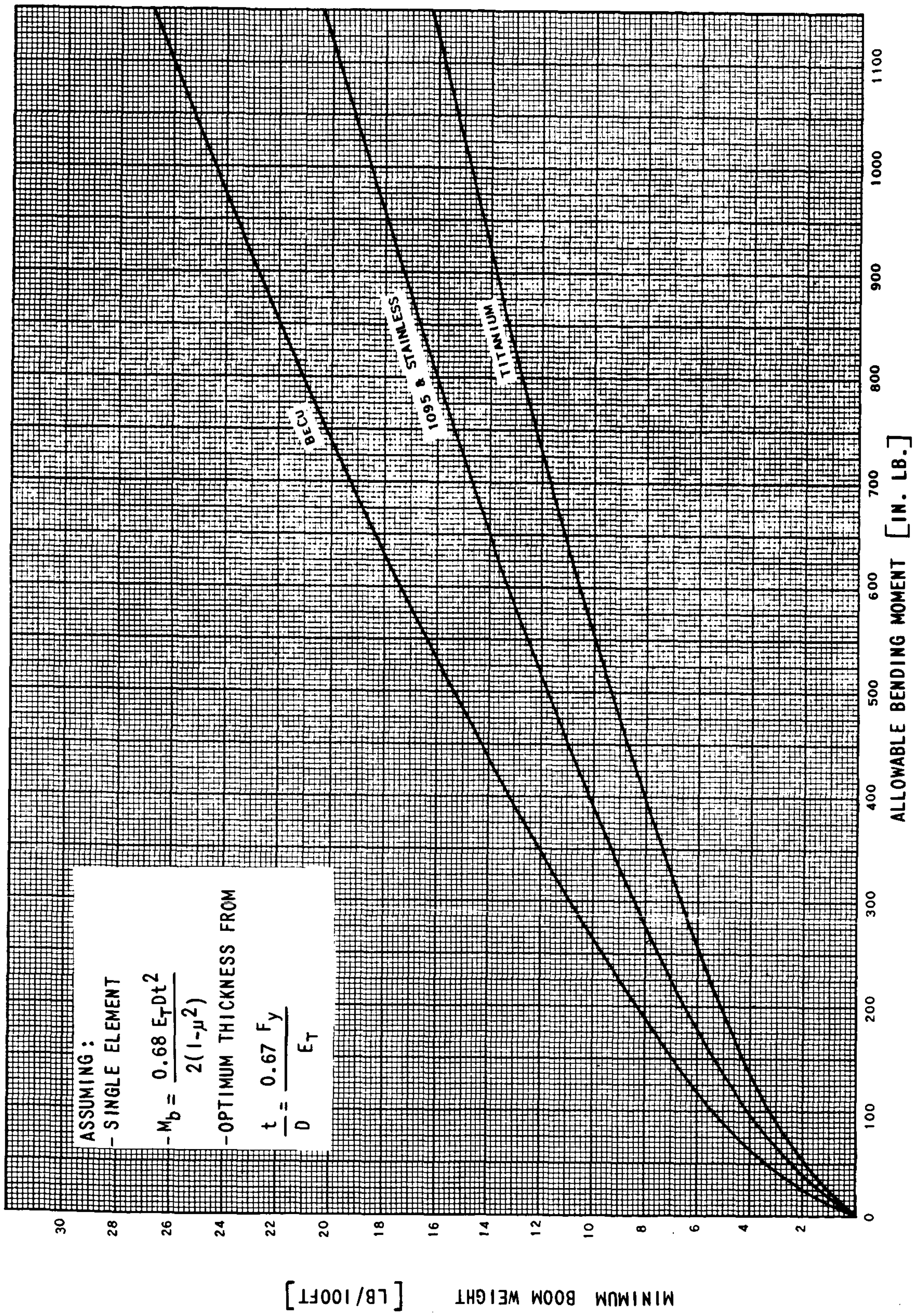

Figure 8. Minimum Boom Weight vs Bending Moment.

(b) FIGURE 5 - MAXIMUM STRIP THICKNESS vs STRIP WIDTH
This figure assumes a 50% reverse factor on the material yield strength using:

$$\frac{t}{D} = \frac{2}{3} \cdot \frac{F_y}{E_T}$$

(c) FIGURE 6 - BOOM WEIGHT vs STRIP WIDTH
This curve assumes the maximum allowable strip thickness from Figure 5.

(d) FIGURE 7 - MAXIMUM BENDING MOMENT vs STRIP WIDTH
This curve assumes the maximum allowable thickness from Figure 5 and a value of K = 0.68 in the formula:

$$M_b = \frac{KE_L Dt^2}{2(1-\mu^2)}$$

This value of K is approximately true for 180° overlap and boom lengths of 10 to 15 feet if ploy support is assumed 90% efficient. The first two curves will give only an order of magnitude for boom strengths, and strength-to-weight ratios.

(e) FIGURE 8 - MINIMUM BOOM WEIGHT vs BENDING MOMENT
This curve assumes maximum strip thickness from Figure 5 and maximum bending moment from Figure 7. Using Figures 7 and 8 and working back to Figure 4, a first approximation as to boom size can be made.

EXAMPLE

Boom Length - 15 Feet

Maximum Bending Moment Applied - 500 in. lb.

From Figure 8, the minimum element weight would be 9.3 lb/100 ft. for the titanium alloy and 11.7 lb/100 ft. for the stainless steel.

From Figure 7 the strip width would be 4.8 in. for the titanium alloy and 5.6 in. for the stainless steel. These widths should be rounded out to:

Titanium alloy - 5.0 in. wide

Stainless steel - 6.0 in. wide

From Figure 6 the maximum boom weight at these rounded out widths would be for titanium alloy W_b = 9.9 lb/100 ft. and for stainless steel W_b = 13.7 lb/100 ft.

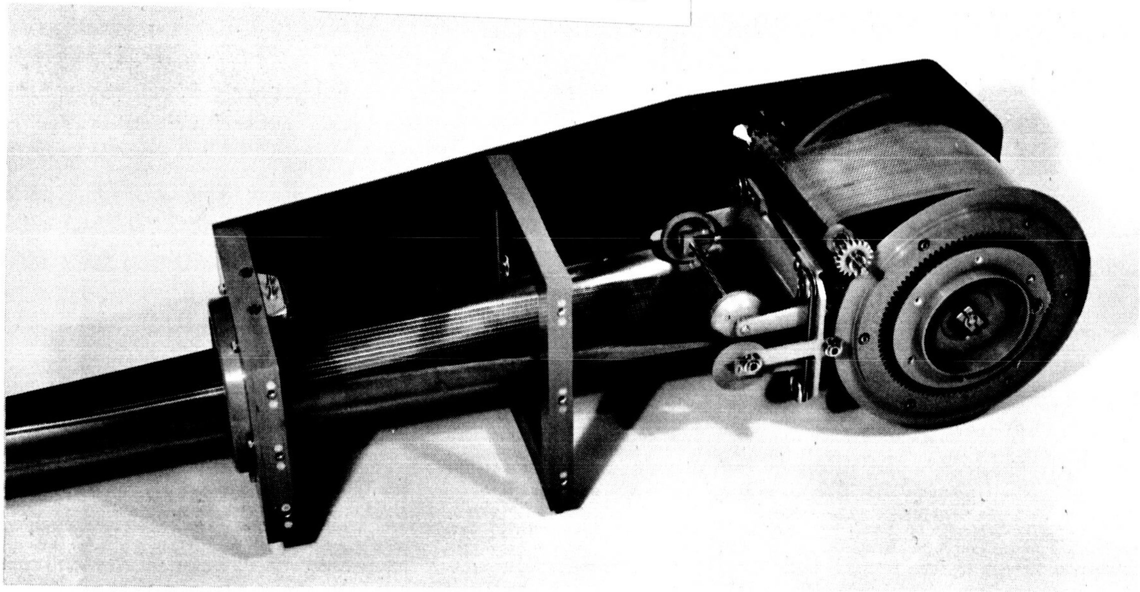

Figure 9. A-26 Extendible Boom Unit (Side View)

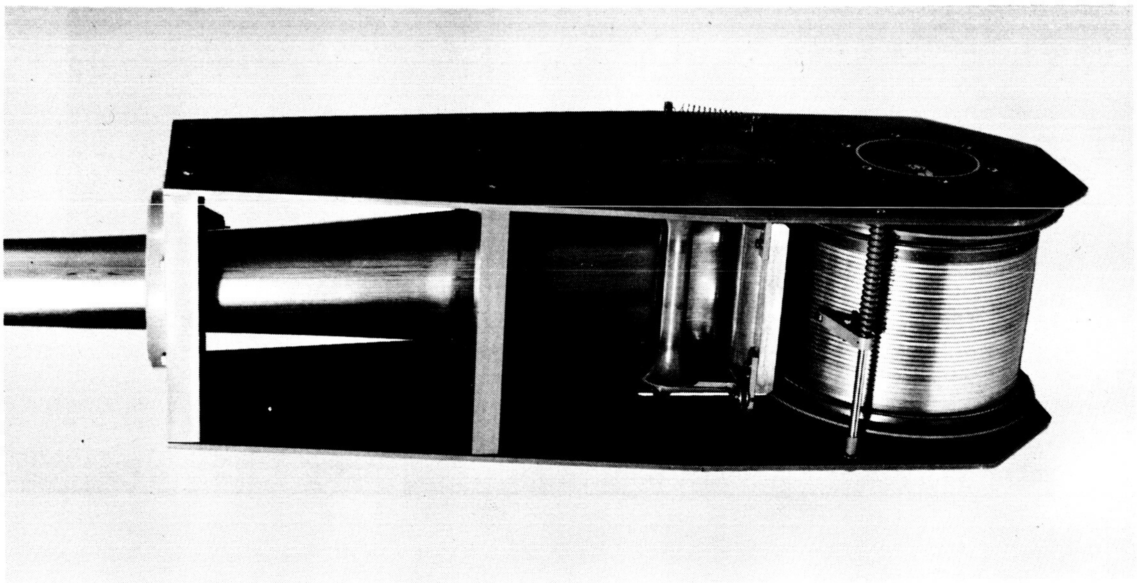

Figure 10. A-26 Extendible Boom Unit (Underneath View).

From Figure 4 we have the boom diameter for 180° overlap, the assumed configuration in the above curves as 1.06-inch diameter for the 5-inch wide strip, and 1.27-inch diameter for the 6-inch wide stainless strip.

Therefore, the choosing of stainless steel as a state-of-the-art material, results in the following:

Boom Material	-	Stainless Steel
Strip Width	-	6.0 in.
Strip Thickness	-	0.006 in.
Boom Diameter	-	1.25 in.
Boom Weight	-	1.95 lb.

END